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Continuous 'stunted' outbursts detected from the cataclysmic variable KIC 9202990 using *Kepler* data

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ABSTRACT

Based on early *Kepler* data, Østensen et al. found that KIC 9202990 showed a 4-h and a two-week photometric period. They suggested the 4-h period was a signature of an orbital period; the longer period was possibly due to precession of an accretion disc and KIC 9202990 was a cataclysmic variable with an accretion disc which is always in a bright state (a nova-like system). Using the full *Kepler* data set on KIC 9202990 which covers 1421 d (Quarter 2–17), and includes 1-min cadence data from the whole of Quarters 5 and 16, we find that the 4-h period is stable and therefore a signature of the binary orbital period. In contrast, the 10–12 d period is not stable and shows an amplitude between 20 and 50 per cent. This longer period modulation is similar to those nova-like systems which show 'stunted' outbursts. We discuss the problems that a precessing disc model has in explaining the observed characteristics and indicate why we favour a stunted outburst model. Although such stunted events are considered to be related to the standard disc instability mechanism, their origin is not well understood. KIC 9202990 shows the lowest amplitude and shortest period of continuous stunted outburst systems, making it an ideal target to better understand stunted outbursts and accretion instabilities in general.

Key words: accretion, accretion discs – instabilities – stars: individual: KIC 9202990 – novae, cataclysmic variables.

1 INTRODUCTION

The *Kepler* satellite observed the same 115 deg^2 field of view, just north of the Galactic plane in Cygnus and Lyra, between 2009 April and 2013 May. It allowed virtually uninterrupted photometry of more than 150 000 stars with 30-min cadence and 512 stars with 1-min cadence at any one time. Although the prime goal of the *Kepler* mission was to discover Earth-sized planets orbiting the host stars habitable zone (e.g. Borucki et al. 2013), it has led to a revolution in the field of asterseismology across the HR diagram (e.g. Chaplin et al. 2014).

Kepler has also provided a unique opportunity to study accreting sources such as cataclysmic variables (CVs) which show flux variations over time-scales ranging from seconds to years or even decades. Early observations such as those of V344 Lyr (Still et al. 2010) showed the potential of *Kepler* to address key questions regarding the nature of the outbursts seen in CVs. CVs contain a white dwarf which is accreting material through Roche lobe overflow from a late-type star. The observed characteristics of the system is largely set by the binary orbital period and the strength of the magnetic field of the white dwarf. *Kepler* has observed dozens of CVs, some of which were known prior to its launch (see Howell et al. 2013), while others were discovered purely by chance (e.g. Barclay et al. 2012; Brown et al. 2015).

Very early in the mission, Østensen et al. (2010) presented initial results of *Kepler* observations of a sample of known or suspected compact pulsators. One of these sources, KIC 9202990, showed a strong modulation on a time-scale of two weeks together with a second much shorter period (∼4 h) superimposed. They presented an optical spectrum which showed Balmer lines in absorption but filled in with emission and appeared to be disc-dominated and similar to nova-like CVs. Østensen et al. (2010) suggested that the 4-h period represented the binary orbital period which would be typical of nova-like CVs which lie predominately above the 2–3 h period gap (see Gänsicke et al. 2009 for an overview of the orbital period distribution of CVs) and has a high mass-transfer rate and an accretion disc in a bright, steady state (see Dhillon 1996 for a review of

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nova-like CVs and also Aungwerojwit et al. 2005). They suggested that the 4-h period was the orbital period and the longer period was due to a precessing disc. McNamara, Jackiewicz & McKeever (2012) noted it was a possible pulsating B star based on an analysis of the light curve.

With the *Kepler* mission now having ended as it was first envisaged, we have taken all the *Kepler* data on KIC 9202990 and set out to determine if the nova-like CV designation can be supported by the much more extensive data set than was available to Østensen et al. (2010).

2 KIC 9202990

KIC 9202990 has a position $\alpha = 18^{\mathrm{h}}56^{\mathrm{m}}08\overset{\mathrm{s}}{.}1 \delta = +45°37'40\overset{\prime\prime}{.}1$ J2000.0 (taken from the Kepler Input Catalog). It was not detected in the *ROSAT* All-Sky Survey, but does not appear to have been in the field of any pointed *XMM–Newton* or *Chandra* observations. It was observed in the Kepler INT Survey (KIS, Greiss et al. 2012a, Greiss et al. 2012b) which obtained $Ugri\mathrm{H}_{\alpha}$ photometry of the majority of sources in the *Kepler* field. The mean photometry and colours of KIC 9202990 are $g = 15.39{\pm}0.04$, $U - g = -0.62$, $g - r = 0.12$, $r - i = 0.15$ and $r - \mathrm{H}_{\alpha} = 0.23$. The latter colour index is consistent with H α in absorption. The UBV Survey of the *Kepler* field (Everett, Howell & Kinemuchi 2012) also indicate a very blue source: $B - V = 0.09$, $U - B = -0.70$. These colours are consistent with other CVs. KIC 9202990 has also been detected using the Catalina Real-time Transient Survey (Drake et al. 2009). There are 69 photometric data points spread over 8 yr showing a mean of $V \sim 15.0 \pm 0.2$ and a range of $V \sim$14.6–15.5.

3 KEPLER PHOTOMETRIC OBSERVATIONS

The vast majority of targets in the *Kepler* field were observed in *long cadence* (LC) mode, where the effective exposure is 27.1 min. A very small number of targets (the targets could be changed every month) were observed in *short cadence* (SC) mode, where the effective exposure is 54.2 s. As the satellite was rotated every 3 months to ensure the solar array was effectively pointed to the Sun, there are short data gaps when data were downloaded from the satellite. KIC 9202990 was observed for 16 'Quarters' (Q2–17), giving almost 4 yr of near continuous data between 2009 June and 2013 May, and it was observed for 7 months using SC mode (Q2/3, Q5/1–3 and Q16/1–3). After the raw data are corrected for bias, shutterless readout smear, and sky background (see Jenkins et al. 2010), time series are extracted using simple aperture photometry (SAP).

The SAP data were extracted from the data files downloaded from the MAST archive[1] and filtered to remove data from time intervals when the data may have been compromised, for instance by enhanced Solar activity, (we filtered data points so that 'SAP_QUALITY=0'). We then normalized each quarter of data so that the mean count rate was unity. To remove systematic trends in the data we used the task `kepcotrend` which is part of the PYKE software (Still & Barclay 2012).[2] We then applied a small offset so that there are no discrete jumps in flux between the different quarters of data. The same steps were applied to the SC data.

[1] http://archive.stsci.edu/kepler

[2] http://keplergo.arc.nasa.gov/PyKE.shtml

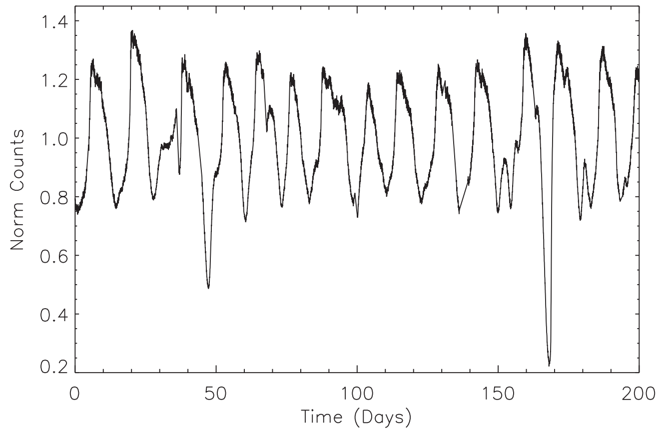

Figure 1. As an example of the flux variations of KIC 9202990 on a time-scale of tens of days, we show a light curve covering 200 d (MJD 55872–56072, 2011Nov 07–2012 May 25). Note the presence of two prominent dips at 45 d and 168 d from the start.

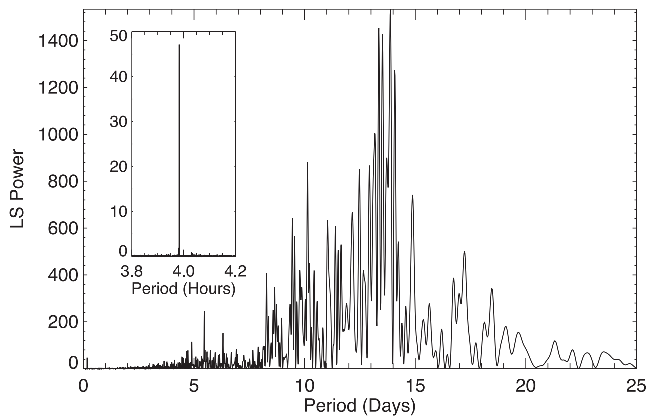

Figure 2. The Lomb–Scargle power spectrum derived using the full LC light curve of KIC 9202990. The many peaks are indicative of the complex nature of the long period (the window function does not show significant side lobes). In the smaller panel, we show the power spectrum centred near the period of the orbital period (3.98 h).

3.1 LC data

To highlight the photometric variability of KIC 9202990 on a time-scale of tens of days, we show 200 d of LC data of KIC 9202990 in Fig. 1. As first reported by Østensen et al. (2010), there is a prominent modulation on a time-scale between 10 and 12 d and a full amplitude which varies between 20 and 50 per cent. We also note the presence of two clear 'dips' in the light curve. We show the Lomb–Scargle power spectrum of the full LC light curve in Fig. 2, which covers 1421 d, but has short gaps every 3 months. The power spectrum is complex but shows four prominent peaks corresponding to periods between 13 and 14 d. This implies the large modulation seen in Fig. 1 is not strictly periodic but quasi-periodic (we call this the 'long' period).

We also determined the length of each cycle by simply determining the time of maximum flux of each long period cycle. The distribution of the duration of each cycle can be approximated with a Gaussian function with a mean duration of 12.5 d with an FWHM of ∼4 d.

We also searched for periodic behaviour on time-scales greater than the long period. Since long-term trends maybe removed when we normalize the light curve on a quarter basis, we used the light

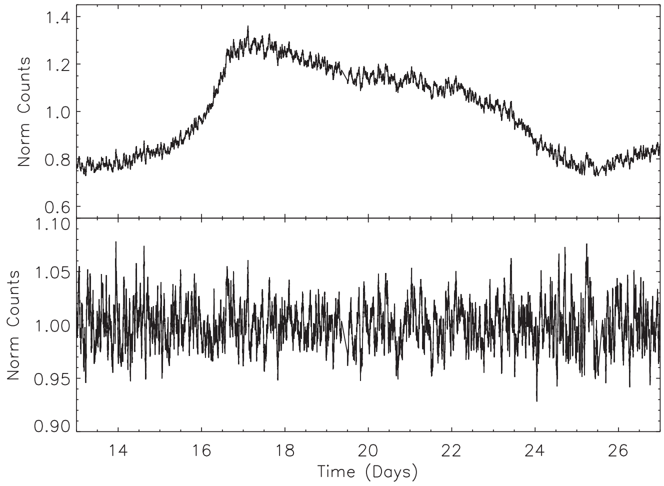

Figure 3. The SC light curve of KIC 9202990, derived from Q5 data, shows one long cycle (top panel). The lower panel shows the light curve after the effects of this long cycle have been removed.

curve which was detrended but not normalized. There is clear peak in the power spectrum at ∼185 d which is due to a modulation with a full amplitude of ∼10 per cent in the light curve. (This period is not seen in the power spectrum of the normalized light curve.) However, we note that this period is half the orbital period of the *Kepler* satellite. Bányai et al. (2013) and Hartig et al. (2014) present studies of *Kepler* observations of long-period variables and find some evidence that year long periods maybe artefacts in the SAP-derived light curve. We therefore add some caution regarding whether the 185 d modulation is intrinsic to KIC 9202990.

3.2 SC data

As noted by Østensen et al. (2010), in addition to the long-period, high-amplitude modulation, there is also a short-period, low-amplitude modulation present in the light curve of KIC 9202990. Although the cadence of the LC data is much lower than the SC data, the signature of the shorter period is seen in the power spectrum of the LC data set (Fig. 2). However, the SC gives a much higher resolution of the short-period modulation. This can be seen in Fig. 3 where we show one complete cycle of the long period and the resulting light curve after this modulation has been removed using the PYKE task `kepdetrend`. We derived the Lomb–Scargle power spectrum of each month of SC data: each power spectrum shows a dominant period at 3.98 h. We then folded each month of data (and also combined data from each quarter) on the ephemeris:

$$T_o = \mathrm{BMJD}55063.816924 + 0.1659404\mathrm{E} \quad (1)$$

As can be seen from the folded light curves (Fig. 4), the shape and phase of the light curves are virtually identical. We fit the LC light curve using a sinusodial wave with a period of 0.165 9404 d and obtained a set of residuals using a 10 cycle fit. Although the residuals show a two-week quasi-period which is almost certainly the result of the changing shape of the orbital period profile (see Section 4), there is no systematic change in the O-C residuals over the course of the LC light curve. This strongly suggests that the 0.165 9404 d period is extremely stable and must be the signature of the binary orbital period (as suggested by Østensen et al. 2010).

4 ORBITAL AND LONG-PERIOD VARIATIONS

The forest of peaks in the periodogram of KIC 9202990 (Fig. 2) suggests that the long period is not stable. In order to investigate this further, we have performed more detailed investigations. The simplest test is to obtain a Lomb–Scargle periodogram of relatively short sections of data in a sliding manner. We show the resulting 'spectrogram' in Fig. 5: it confirms that the long period is not stable and shows other periods that appear to be transient in nature.

We then carried out a more sophisticated analysis using both the Q5 and Q16 SC data sets which are both approximately 90 d in length. We perform the same analysis on each light curve separately, which aims to measure the similarity of the orbital light-curve shape as a function of their separation in time. Our analysis proceeds as follows: (i) pick two non-overlapping pieces of light curves, each 2 d (giving 12 orbital cycles) long, separated by a random amount of time (from 2 d up to the length of the data set); (ii) fold these two subsections of light curves over the 4-h orbital period and bin each of these into 50 orbital phase bins; (iii) compute the sum of squared differences of the binned light curves, and (iv) repeat this 100 000 times. As a result, we have a measure of the difference between orbital light curve shapes as a function of their separation in time. Finally, we have binned the results in 0.1 d time bins: in both data sets, we see a minimum near 10–12 d separation and its multiples (Fig. 6). This strongly suggests that the orbital light curve shape is indeed modulated on a 10–12 d period, which corresponds to the 20–50 per cent modulation seen in the light curves (Fig. 1).

Lastly, we took the data from Q5 (which has the most complete quarter of data) and split the data up into long cycles. This was done by manually selecting the start and end point of each cycle and splitting this cycle into ten equally phased bins. We then phased the data in the same way as before and show the resulting folded light curves in Fig. 7. In the first cycle, the light curve folded on the orbital period gradually becomes more structured having a clear peak in brightness and a peak-to-peak amplitude of ∼4 per cent, before the variation becomes less defined with a lower amplitude of variation. Over the next cycles the process repeats in a similar, but not identical, manner, with the shape of the folded light curve changing over successive orbits. It is clear that the data folded on the orbital period can change significantly in appearance over the long-term cycle.

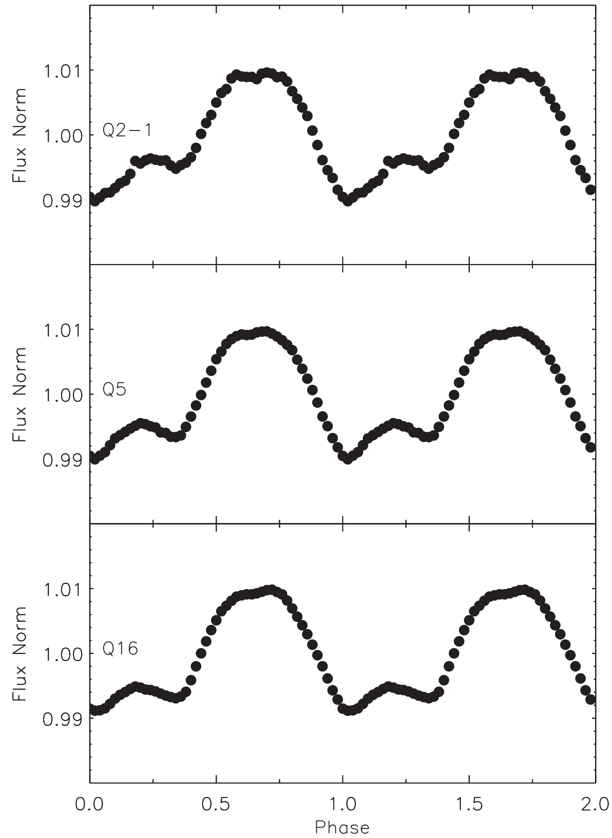

Figure 4. The SC data of KIC 9202990 taken from three separate quarters in time have been folded on the ephemeris shown in equation (1). The repeatability of the resulting profiles indicates that the 4-h period is a signature of the orbital period.

5 DISCUSSION

KIC 9202990 displays optical photometric variability on two distinct time-scales: the 4-h orbital period and a quasi-period of 10–12 d which we have termed the long period. As indicated earlier, the 4-h orbital period is typical of nova-like CVs with bright steady state accretion discs, which lie predominately above the 2–3 h period gap. What makes KIC 9202990 unusual is the amplitude of the long-period modulation and its phase dependence which does not resemble classical outbursts seen in CVs.

Østensen et al. (2010) suggested that the long period was due to a precessing disc. However, the disc would need to have a large tilt, or alternatively an extended outer rim of varying height, to account for the large amplitude variation. This would then give rise to negative superhumps since the accretion disc bright spot should sweep first across one face of the disc, and then the other and hence varies in depth in the potential well of the white dwarf (a negative superhump has a period a few per cent shorter than the orbital period; see Thomas & Wood 2015). Positive superhumps show a period longer than the orbital period by a few per cent, but are only seen in systems with a mass ratio $q = M_1/M_2 \lesssim 0.35$ (see Wood et al. 2011). For a CV with a orbital of 4 h, q is not likely to be $\lesssim$0.35 (e.g. Knigge, Baraffe & Patterson 2011) and therefore is not expected to show positive superhumps.

In principal the 4-h period, we observe could be a signature of the negative superhump but this period is very steady and the O-C residuals are very small with no trends. The precession period is a function of the moment of inertia of the disc, and if the mass distribution changes, then the precession period will change, and as a result the negative superhump period will change, causing variations in the O-C. These variations are seen in two other CVs observed using *Kepler*, V344 Lyr and V1504 Cyg, where the residuals can show cyclic changes over the course of the outburst cycle (Osaki

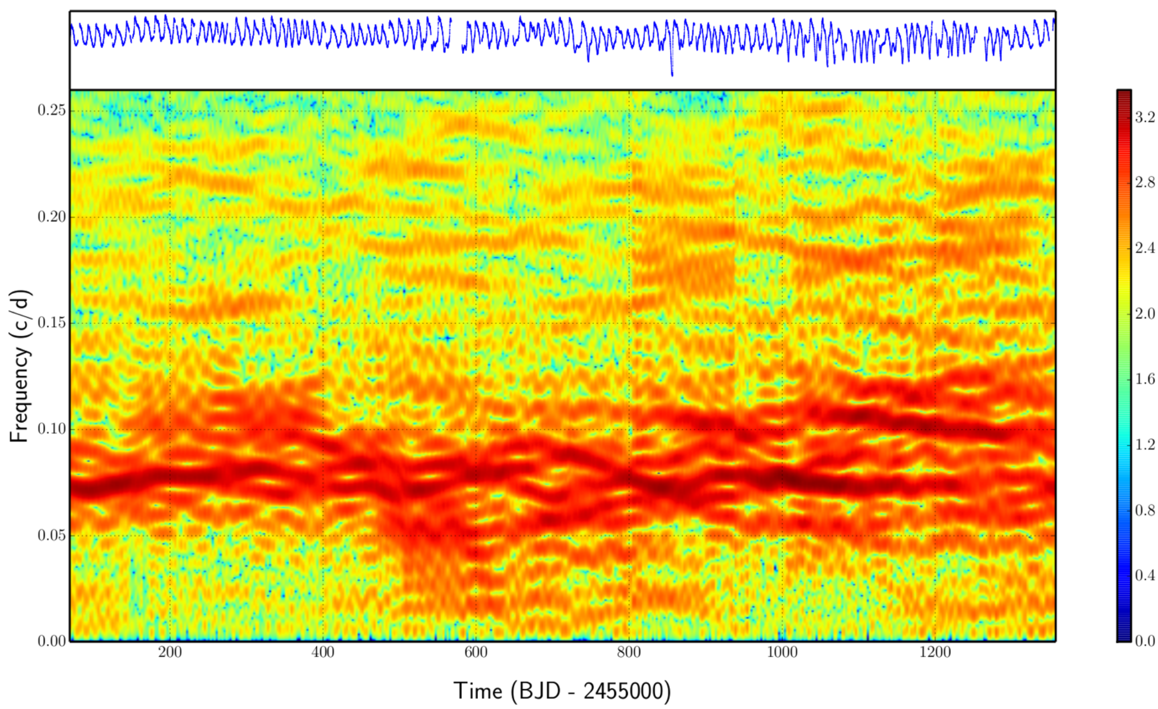

Figure 5. Using a sliding Lomb–Scargle periodogram, we show how the long period varies over the course of the observations. The top panel shows the *Kepler* light curve of KIC 9202990 and the right-hand panel shows the power of the periodogram. The frequency of the dominant peak in the periodogram clearly changes over time.

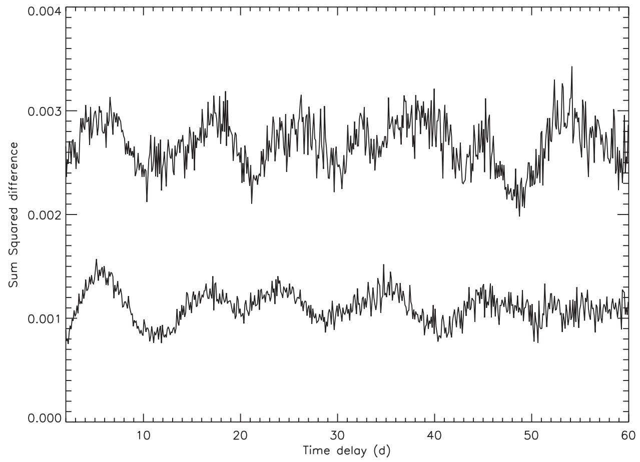

Figure 6. We show the results of measuring the difference in the orbital light curves as a function of time for Q5 SC data (top) and Q16 SC data (bottom). This indicates the longer period is modulated on a quasi-period of 10–14 d (see text for details).

& Kato 2013). We also note that the amplitude of the superhump variation in V344 Lyr is much greater than the amplitude of the orbital variation (cf. Still et al. 2010). We therefore consider it highly unlikely that the long-period modulation is due to a precessing disc.

The profile of the long-period modulation (cf. Fig. 3) shows a relatively slow rise to maximum brightness, whereas dwarf nova outbursts show a much more rapid increases to maximum (and a greater amplitude (>1 mag). There are, however, a small group of nova-like CVs which show 'stunted' outbursts with amplitudes up to 1 mag (e.g. Honeycutt, Robertson & Turner 1995, 1998; Warner 1995). Warner (1995) notes that for a steady-state accretion disc to produce a modulation amplitude of 0.7–1.0 mag would require the mass-transfer rate to change by a factor of 10 over the cycle, implying a changing mass-transfer rate was not the cause of the modulation. Honeycutt (2001) observed nova-like and dwarf nova using a small robotic telescope and conclude that the cause of the periodic modulation seen in some nova-like CVs is essentially the same as dwarf nova outbursts.

We show in Fig. 8 the relationship between the amplitude of stunted outbursts and their period of modulation using the work of Honeycutt (2001) and add the new value for KIC 9202990. Although there is a clear spread between amplitude and period of the stunted outburst systems, there is a weak trend with short periods giving smaller amplitude variations. KIC 9202990 is at the short-period end of the distribution and has the lowest amplitude. There is no correlation between the orbital period and the recurrance time of the outbursts nor the amplitude of the outburst. KIC 9202990 bears some similarity to a CV also in the *Kepler* field, KIC 9406652 (Gies et al. 2013), which has an orbital period of 6.1 h but also shows outbursts with amplitude ∼0.6 mag on a recurrence time-scale of 27–84 d.

Another feature of some of these stunted dwarf novae is the presence of 'dips' seen in the light curve. Honeycutt et al. (1998) show that multiple dips can be seen in systems which have a depth of 0.2 to >0.5 mag with an FWHM ranging from 2 to 50 d. Our LC observations of KIC 9202990 indicate two obvious dips

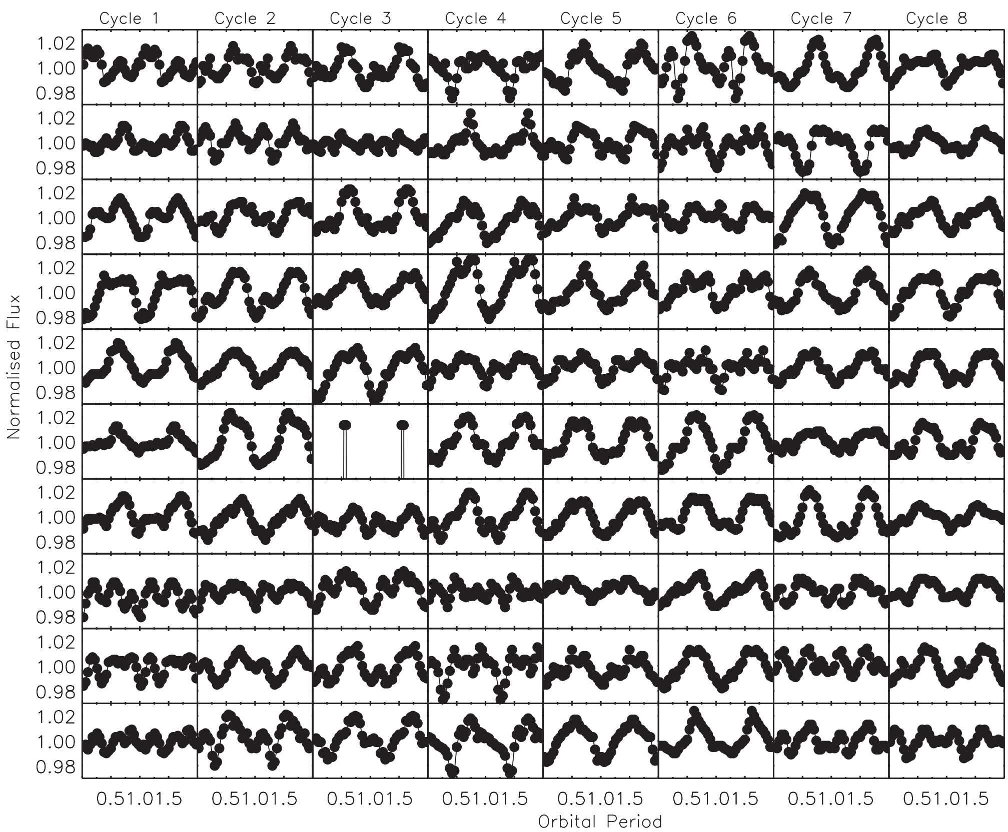

Figure 7. We have taken the SC data from Q5, removed the trend caused by the long-period variation, but split up the data so that each subsection contains one long-period cycle (arranged from left to right). We have then further split these subsections into 10 bins (and arranged from top to bottom) and folded these data on the orbital period. (One panel has only two points.) It is clear that the profile of the folded orbital light curve changes significantly over the long cycle.

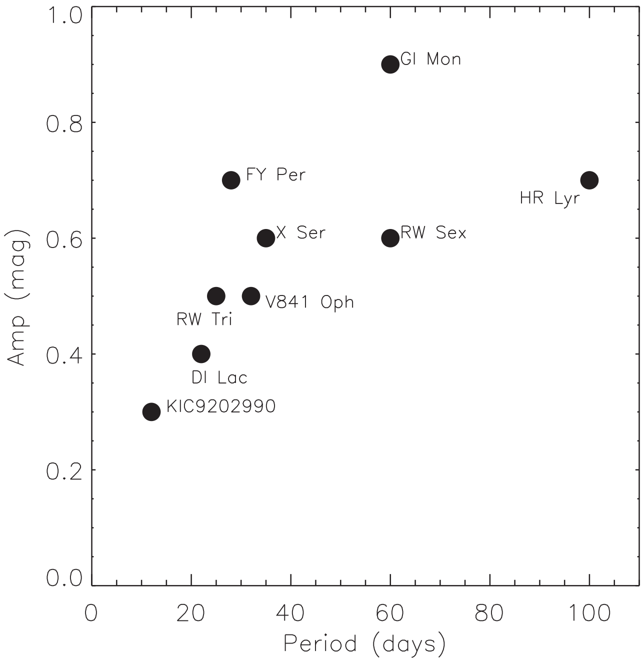

Figure 8. We compare the amplitude and period of the long period found in KIC 9202990 with the amplitude and time-scale of the repeating stunted outbursts of nova-like sources (taken from Honeycutt 2001). For comparison KIC 9406652 (Gies et al. 2013) shows ~0.6 mag outbursts on a time-scale between 27 and 84 d. KIC 9202990 has the shortest time-scale for stunted outbursts and the smallest amplitude.

(see Fig. 2) of depths 0.4 and 0.6 mag with FWHM of 2–3 d. These dips share some resemblance to the dips seen in the nova-like subclass of CVs the VY Scl stars, although the duration of these dips are typically tens of days and are deeper than seen in KIC 9202990. They are thought to be due to temporary reduction in mass-transfer rate which maybe related to activity on the secondary star (see for instance Howell et al. 2000 and Kafka & Honeycutt 2005).

6 CONCLUSIONS

We have explored the photometric properties of KIC 9202990 which was identified as a nova-like CV exhibiting a clear modulation on a 4 h and a 10–12 d quasi-period using *Kepler* data by Østensen et al. (2010). We find that the 4-h period is stable and must be the orbital period. The longer period is not stable and given the absence of negative superhumps in the light curve, we consider it highly unlikely it is due to the precession of an accretion disc. However, we find that the characteristics of this long period is very similar to the 'stunted' outbursts seen in a small number of nova-like systems. KIC 9202990 would be placed on the short-period and low-amplitude end of the distribution in these sources. Medium-resolution optical spectroscopy which could adequately resolve the orbital period over the course of the long period would allow doppler tomograms to be made as a function of the long period which would indicate how the brightness of the disc changes. Another avenue to explore will be to model the brightness changes over the long term using smoothed particle hydrodynamical simulation codes such as described for instance in Larwood et al. (1996), Simpson (1995) and Thomas & Wood (2015).

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